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# PROVISIONAL APPLICATION FOR PATENT COVER SHEET

This is a request for filing a PROVISIONAL APPLICATION FOR PATENT under 37 CFR 1.53(c).

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09/905693  
11/14/00



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<input type="checkbox"/> Additional inventors are being named on the ___ separately numbered sheets attached hereto					
TITLE OF THE INVENTION (280 characters max)					
SEQUENTIAL DIVERSITY IMAGING					
Direct all correspondence to: CORRESPONDENCE ADDRESS					
<input type="checkbox"/> Customer Number		<input type="text"/>		<div>Place Customer Number Bar Code Label here</div>	
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ENCLOSED APPLICATION PARTS (check all that apply)					
<input checked="" type="checkbox"/> Specification		Number of Pages		<input type="checkbox"/> CD(s), Number	
<input checked="" type="checkbox"/> Drawing(s)		Number of Sheets		<input type="checkbox"/> Other (specify)	
<input type="checkbox"/> Application Data Sheet. See 37 CFR 1.76					
METHOD OF PAYMENT OF FILING FEES FOR THIS PROVISIONAL APPLICATION FOR PATENT					
<input checked="" type="checkbox"/> Applicant claims small entity status. See 37 CFR 1.27.		FILING FEE		AMOUNT (\$)	
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The invention was made by an agency of the United States Government or under a contract with an agency of the United States Government.					
<input checked="" type="checkbox"/> No.					
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Respectfully submitted,

SIGNATURE Richard Menezly

Date 10/7/00

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REGISTRATION NO.  
(if appropriate)  
Docket Number:

26,620

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This collection of information is required by 37 CFR 1.51. The information is used by the public to file (and by the PTO to process) a provisional application. Confidentiality is governed by 35 U.S.C. 122 and 37 CFR 1.14. This collection is estimated to take 8 hours to complete, including gathering, preparing, and submitting the complete provisional application to the PTO. Time will vary depending upon the individual case. Any comments on the amount of time you require to complete this form and/or suggestions for reducing this burden, should be sent to the Chief Information Officer, U.S. Patent and Trademark Office, U.S. Department of Commerce, Washington, D.C. 20231. DO NOT SEND FEES OR COMPLETED FORMS TO THIS ADDRESS. SEND TO: Box Provisional Application, Assistant Commissioner for Patents, Washington, D.C. 20231.

## Sequential Diversity Imaging

Inventor: Robert A. Gonsalves, Woburn, Mass.

### Abstract

Diversity imaging uses two or more diverse images of an object to enhance the detected images and/or to improve the image quality of an optical system. The method estimates both the unknown object and the parameters of any disturbances in the optical system. The estimated parameters can be used to control an adaptive optic in the optical system so as to sharpen the image. In this invention we use time-sequential images from such an optical system and time sequential diversities to develop control signals for the adaptive optic. We show that the required sequential diversities are the sequential changes in the adaptive optic.

### References Cited

#### Us Patent Documents

3,979,585	09/1976	O'Meara, Adaptive imaging telescope with camera-computer transform image quality sensing and electro-optic phase shifting
3,923,400	12/1975	Hardy, Real-time wavefront correction system
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4,309,602	01/1982	Gonsalves, et. al. Wavefront sensing by phase retrieval
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6,084,227	07/2000	Rhodes Method and apparatus for wide field distortion-compensated imaging
6,107,617	08/2000	Love, et. al. Liquid crystal active optics correction for large space based optical systems

09905693-11400

## BACKGROUND OF THE INVENTION

The present invention relates to imaging through a random medium such as the turbulent atmosphere or the slowly changing optics of a camera; and how to combat the deleterious effects of that medium, in a real-time and an automatic way. We show how to determine the distorting wavefront caused by the medium and how to control an adaptive optic in the optical system to eliminate that wavefront.

Diversity imaging uses one or more of the images, each with a known diversity (phase, wavelength, or spatial shift), to deduce both the unknown object and the parameters of the medium. Gonsalves and Devaney held the first patent of this kind and the method was used by Gonsalves and others to deduce the flaw in the Hubble Space Telescope. In the usual embodiment of this method the diversity is a quadratic phase shift, which can be introduced by defocusing the optical system. Love, et al., Duncan, et al., and Paxman hold current patents which use phase diversity.

Unlike the patents by Gonsalves and others, this invention uses only the measured image sequence itself, as data. No additional image, such as a second, defocused image is required. Successive images form the multiplicity of images required for diversity imaging and the changes to the adaptive optic are the diversities.

This novel approach eliminates the need for any other mechanisms. It applies to any adaptive optic and to any digital camera. The innovations are the use of sequential images as the diversity images and the use of a sequential diversity processor to control the adaptive optic.

Further background references are listed below:

### References

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2. R. Gonsalves, "Phase Retrieval from Modulus Data", *J. Opt. Soc. of Am.* 66, 961 (1976).
3. J. Fienup, "Phase retrieval algorithms: a comparison," *Ap. Opt.*, 21, 2758 (1982)
4. R. Gonsalves, "Phase Retrieval and Diversity in Adaptive Optics", *Opt. Eng.*, 21, 829 (1982)
5. B. Ellerbrock and D. Morrison, "Linear methods in phase retrieval," *SPIE Proc.* 351, 90 (1982).
6. M. Teague, "Deterministic phase retrieval: a Green's function solution," *J. Opt. Soc. of Am.* 73, 1434 (1983).
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8. R. Paxman and J. Fienup, "Optical misalignment sensing and image reconstruction using phase diversity," *J. Opt. Soc. of America*, A 5, 914 (1988)
9. F. Roddier et al., "A Simple Low-Order Adaptive Optics System For Near-Infrared Applications", *Publications of the Astronomical Society of the Pacific*, 103, 131 (1991).
10. J. E. Graves et al., "The University of Hawaii adaptive optics system: III The Wavefront Curvature Sensor", *SPIE Proc.*, 1542, 262 (1991).
11. R. Kendrick, D. Acton, A. Duncan, "Phase-diversity wave-front sensor for imaging systems," *Appl. Opt.* 33, 6533 (1994).
12. M. A. Voronstov and V. P. Sivokon, " Stochastic parallel-gradient-descent technique for high-resolution wave-front phase-distortion correction," *J. Opt. Soc. Am. A*, 15, 2745 (1988).

## BRIEF DESCRIPTION OF THE DRAWINGS:

Fig. 1 is a combined block-pictorial representation of an imaging system which uses an adaptive optic and a sequential diversity processor, in accordance with the invention.

Fig. 2 is a block diagram of the sequential diversity processor, showing the input images from a detector and the output control signals for the adaptive optic.

Fig. 3 shows a computer simulation of the invention as it would apply to the imaging of a point source, like a star, imaged through a turbulent atmosphere.

## DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

The detector seen in both Fig. 1 and in Fig. 2 is one in which the picture is captured as discrete picture elements - essentially, a digital camera. We propose no new detecting mechanism for the camera; digital cameras exist and are improving in sensitivity and resolution at a dramatic pace.

The adaptive optic (AO) shown in both Fig. 1 and in Fig. 2 is a high-resolution device which allow a wide range of correction mechanisms, such as Zernike polynomial fitting of a complicated wavefront. It is similar to the sophisticated systems currently installed on national telescopes and it has capabilities well beyond the automatic focussing and registration mechanisms in consumer camcorders. These sophisticated AO systems improve image quality by about a factor of ten. They will almost certainly appear in consumer products, after the cost of adaptive optics decrease and after simple, real-time control mechanisms are invented.

The AO in these figures is used to cancel the wavefront distortion,  $W$ . Thus, to be effective, the optical system of Fig. 1 must sense the wavefront. There are five well-known mechanisms for wavefront sensing, which we review here. The five are as follows:

1. Dithering. This method continuously changes the adaptive optic and monitors the image quality of the observed image. The method was patented by O'Meara, who made slowly varying changes to each channel of the adaptive optic, modulated each channel, demodulated the image quality in each channel, and controlled the adaptive optic with the set of image qualities. A recent improvement, stochastic parallel-gradient-descent, has been proposed by Voronstov and Sivokon (Reference 12). They make random changes in all channels and, over time, determine which average changes improve the image quality.
2. Shearing Interferometer. This method uses a reference beam to create an interference pattern which describes the unknown wavefront. Hardy was the first to patent a wavefront sensor based on this device. It has been used successfully in several astronomical installations. Its major drawback is the extra measuring equipment, including a laser-based interferometer, that has to be installed.
3. Shack-Hartmann Sensor. This device uses an array of lenses to image small sections of the wavefront onto a detector. Shifts in the small images are caused by local tilts in the waveform. From these tilts one reconstructs the wavefront. Feinleib held the first patent. A major drawback is the requirement for the lenslet array and sensors.

4. Curvature Sensing. This uses two or more images, measured along the path of the optical system. The local curvature of the propagating wave is determined and it is propagated, by computer simulation, back to the aperture. The computer-generated phase controls an adaptive optic. The method was proposed by Roddier and related patents were awarded to Gaffard, et. al and Rafanelli, et. al.. A system of this type is in use on a telescope in the state of Hawaii. References 6, 7, 9 and 10 describe systems of this kind.

5. Phase retrieval and diversity. Our invention is similar to these, in that they use digital imagery, an adaptive optic, and multiple images. The method was first suggested by Gonsalves (Reference 2). References 1-5, 8 and 11 use phase retrieval and/or diversity.

Many inventors have tried to use post-processing of a series of images to enhance the composite. Patents to Rhodes fall into this category. While such techniques may be useful if the data are already captured and no adaptive optic was available during measurement, this inventor teaches, "If you want a good picture, take a good picture." This implies that it is far better to improve the image in its taking than to try to improve the image by computer processing, after the fact.

Referring to Fig. 1 and Fig. 2, we use the following notation:

$W(k)$  = Unknown distorting wavefront at time  $k$ .

$T(k)$  = Phase put on the AO at time  $k$ .

$C(k)$  = Compensated phase to be estimated by a diversity algorithm

$$= W(k) + T(k) \quad (1)$$

$I(k)$  = Measured image at time  $k$ .

$D(k)$  = Diversity phase.

We consider a diversity algorithm where  $I(k-1)$  is the first image and  $I(k)$  is the diversity image. With this convention the diversity phase is the change in the AO phase from time  $k-1$  to time  $k$ . Thus,

$$D(k) = T(k) - T(k-1). \quad (2)$$

The phase diversity algorithm is set up to estimate  $C(k)$ , the compensated phase at time  $k$ . Call the estimate  $Q(k)$ .  $Q(k)$  is, from equation (1),

$$Q(k) = W1(k) + T(k), \quad (3)$$

where  $W1(k)$  is an estimate of  $W(k)$ , the unknown phase at time  $k$ . (We know  $T(k)$ , so it need not be estimated.) At time  $k+1$  we would like to set the AO phase to the negative of the unknown wavefront at time  $k+1$ . We do not know  $W$  at time  $k+1$  but we do have an estimate

of the wavefront at time  $k$ , namely,  $W1(k)$ . This will be a good estimate of  $W(k+1)$  if AO updates are well within the time constant of the changing medium. Thus, we set

$$T(k+1) = -W1(k), \quad (4)$$

which will tend to cancel the wavefront distortion at  $k+1$ .

Solving (3) for  $W1(k)$  and substituting it into (4), we have

$$T(k+1) = -Q(k) + T(k),$$

which implies

$$T(k) = -Q(k-1) + T(k-1). \quad (5)$$

Turning to the diversity phase, we put (5) into (2) to get

$$\begin{aligned} D(k) &= (-Q(k-1) + T(k-1)) - T(k-1) \\ &= -Q(k-1). \end{aligned} \quad (6)$$

This is the specification for the diversity phase at time  $k$ .

Finally, we put (6) into (5) to get a new expression for the AO phase:

$$T(k) = T(k-1) + D(k). \quad (7)$$

Equations (6) and (7) give us the recipe we sought. The AO phase,  $T(k)$ , is the previous AO phase plus the diversity phase,  $D(k)$ ; and the diversity phase is the negative of the diversity algorithm's output at time  $k-1$ .

These equations are expressed in block diagram form in Fig. 2. The inputs to the diversity algorithm are images  $I(k-1)$  and  $I(k)$ ; the output is  $Q(k)$ , an estimate of the compensated phase; the phase diversity is  $D(k)$ ; and a feedback loop calculates  $T(k)$ .

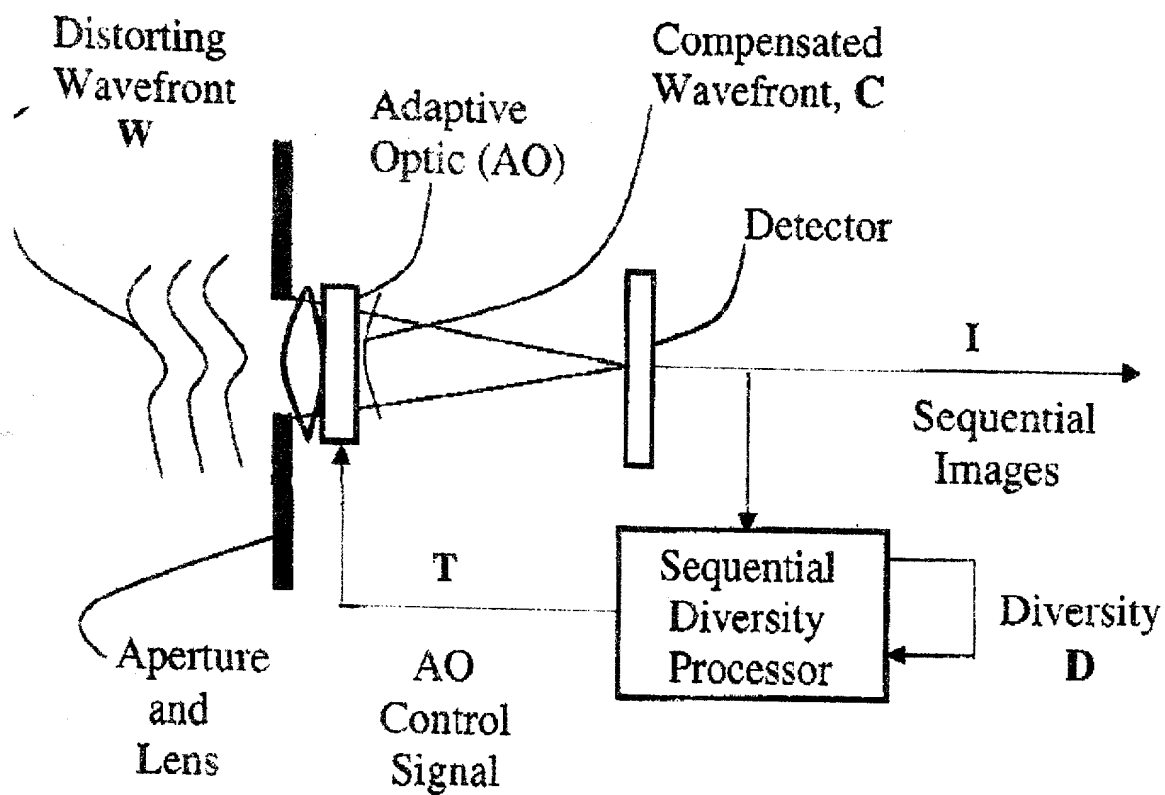
Fig. 3 shows a computer simulation of 24 cycles of the sequential diversity imager. The object is a point source, such as a star. The first observed image of the star is in the lower left of Fig 3. The compensated image is directly above. The last pair is in the upper right. The lower rows show how the star "twinkles" over time. Each uncompensated image is called a speckle pattern and is characteristic of a star imaged through the earth's atmosphere.

A measure of the image quality is the Strehl ratio, i. e., the peak value of the aberrated star image to the peak value of an unaberrated star image. Higher Strehl ratio means higher image quality. For the 24 images shown, the average Strehl ratio is 0.045.

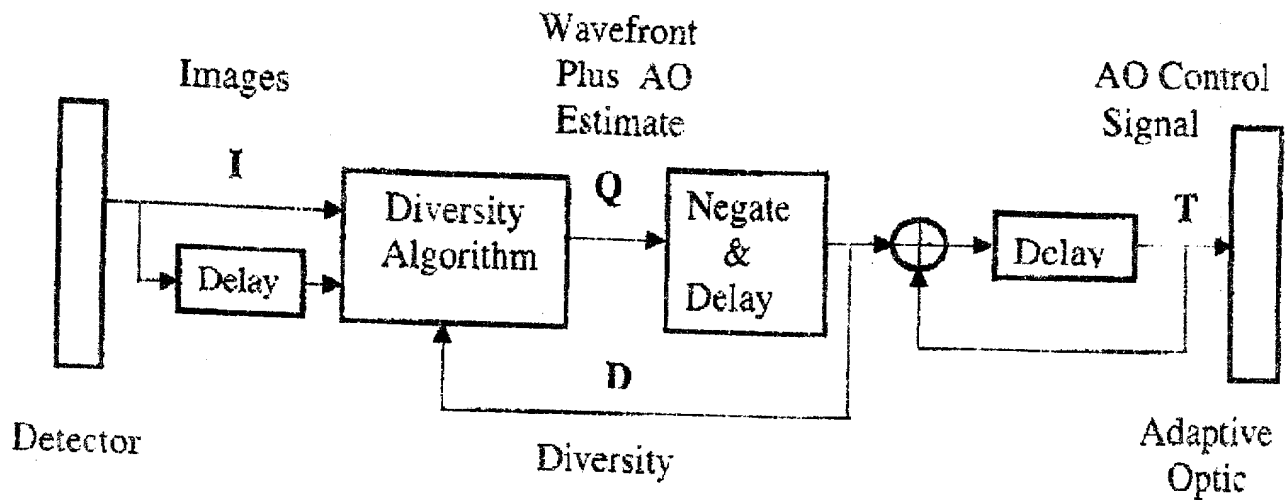
The sequential diversity imaging technique produced the images shown directly above each twinkling image. The average Strehl ratio for the compensated images is 0.467. This is an improvement of about a factor of 10.



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**Fig. 1 Sequential Diversity Imager**

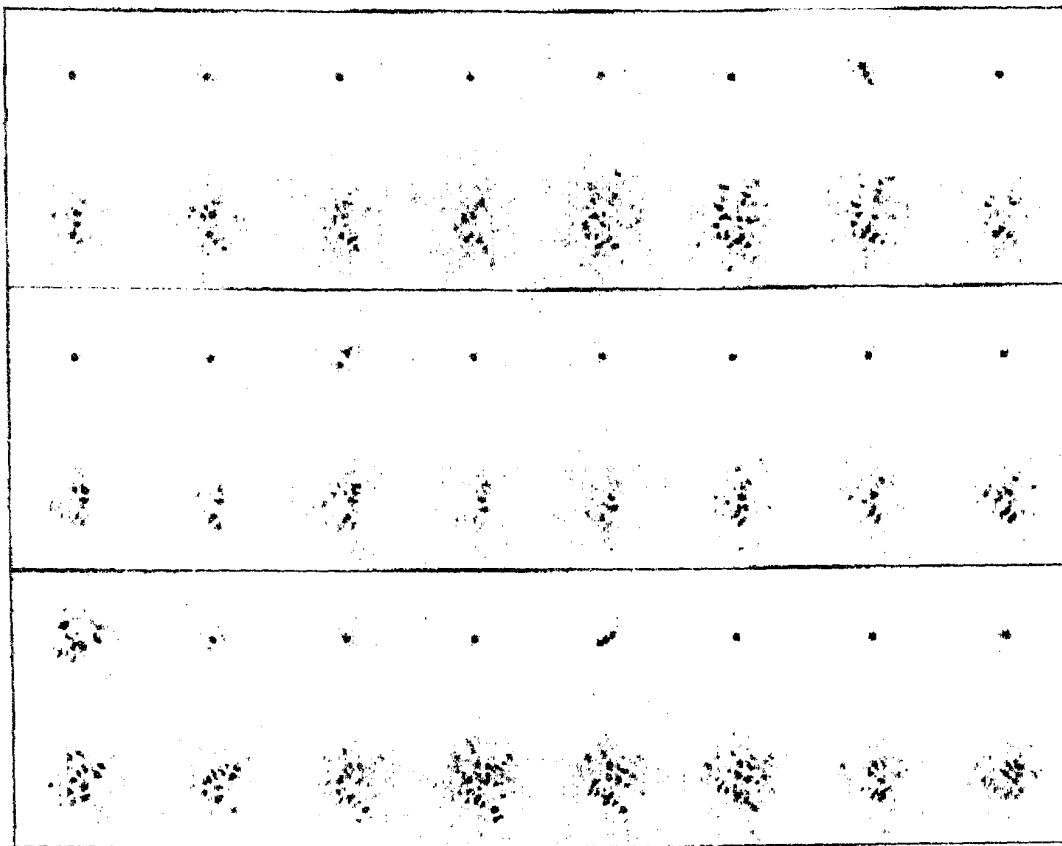


$$D(k) = -Q(k-1)$$

$$T(k) = T(k-1) + D(k)$$

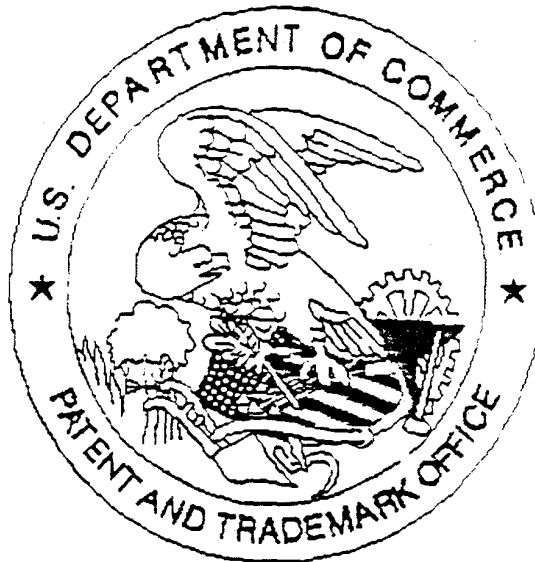
**Fig. 2 Details of the Sequential Diversity Processor**

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**Fig. 3. Computer simulation of 24 cycles of Sequential Diversity Imaging**  
First image pair is in the lower left, last is in the upper right  
Lower rows are uncompensated, upper rows are compensated

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